Development of a Butterfly-style Flapping Robot with a Posture Control Mechanism by Varying the Ratio of Down and Up Stroke Times

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Abstract
In this paper, we develop a butterfly-style flapping robot that has different timings between down and up strokes for posture control, which are based on the flapping characteristics of a butterfly. A butterfly flies upward during the down stroke and forward during the upstroke using posture control. This trajectory resembles a staircase pattern. The flight pattern is influenced by the ratio between the time periods of the down and up strokes during a flapping cycle. To better understand the dynamic effects, we developed a flapping mechanism to mimic this varied stroke timing based on a quick-return mechanism and validated it via motion analysis. A numerical simulation was used to investigate the relation between the ratio of down and up stroke times and posture control of a butterfly. The results showed that the proposed mechanism reproduced observed behavior by incorporating the difference between down and up stroke times for a butterfly-style flapping robot. Furthermore, the simulation indicated that a butterfly tended to fly upward when the down stroke time was longer than that of upstroke, and downward in opposite case.

Key words
flapping robot, ratio between down and up stroke times, quick-return mechanism, posture control


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1 Introduction

In recent years, flying robots such as multi-rotor helicopters have been actively developed for practical applications [1]–[4]. Although the size of these common flying robots ranges from several tens of centimeters to a few meters, there is interest in designing smaller robots which can pass through narrow spaces. To this end, flapping robots modeled after small birds (e.g., hummingbirds) [5], [6] or insects (e.g., flies) [7]–[10] have been developed. However, these robots have not achieved practical flight because it is difficult to incorporate a battery, complex link mechanisms, and actuators that drive wings, and control postures within such a small body. Although insects control their posture during flight by flapping, lead-lag, and feathering of the wings, it is difficult to mimic these motions in insect-scale robots. Therefore, constructing a posture control system in a simple and lightweight manner is necessary to achieve practical flight in small flapping robots.

To overcome such challenges, we recently developed a butterfly-based small flapping robot that has a low flapping frequency of approximately 10Hz and a few degrees of freedom of the wings [11]. The flapping robot is similar in size to that of a butterfly, i.e., its wingspan is almost 115mm, wing chord length is 45mm, and total mass, including an actuator, is less than 500mg. Our flapping robot has a large flapping angle of 80deg to -60deg and a mechanism that realizes both flapping and lead-lag motion by an actuator. These allow the flapping robot to take off from an airspeed of 0m/s, fly upward during the down stroke, and then forward during the upstroke. This staircase pattern of flight mimics the trajectory of a butterfly. Furthermore, we investigated the flight characteristics of different flapping and initial body pitch angles for posture control by performing hardware experiments and numerical simulations [12]. The results indicated that the difference between the timings of a down stroke and an upstroke affects the posture control of a butterfly. Therefore, further development could involve construction of a butterfly-style flapping robot that is easier to operate via controlling a combination of parameters, such as flapping and initial body pitch angles and the ratio between down and up stroke times.

In this paper, we present a butterfly-style flapping robot with a mechanism that generates a difference in the ratio between the down and up stroke times based on a quick-return mechanism. We validate its mechanism by performing experiments and analyzing the flight characteristics using numerical simulation.

This paper is organized as follows: Section 2 describes a butterfly-style flapping robot with a mechanism to generate a difference between the down and up stroke times. Section 3 demonstrates the performance of the stroke mechanism by physical experiments. Section 4 shows an analysis of the flight characteristics for different ratios of the down and up strokes via numerical simulations. Section 5 presents a conclusion of the paper and outlines future work.

2 Butterfly-style flapping robot

2.1 Flight characteristics of a butterfly

Figure 1 shows a swallowtail butterfly (Papilio xuthus) as a model for a flapping robot and a typical takeoff motion captured by high-speed camera (DITECT Co., Ltd.). The red line in Fig. 1 denotes the trajectory of the center of the thorax of a butterfly. This figure shows that a butterfly flies upward during down stroke and forward during upstroke such as a staircase pattern. Since a butterfly flaps the overlapping fore and hind wings in phase, it is difficult to freely change the angle of attack of each wing independently like a dragonfly. Therefore, the butterfly is thought to change its posture by varying the angle of attack of its entire body. In order to investigate the posture control mechanism of a butterfly, we focus on the relation between flapping and body pitch angles. Definitions of these angles are shown in Fig. 2.

Figure 3 shows the flapping and body pitch angles during takeoff. A flapping cycle comprises of down and up strokes. The flapping frequency was approximately 10Hz. The ratios of the down and up strokes were 58% and 42% in a first flapping cycle, and then 59% and 41% in a second flapping cycle respectively. These show that the ratio
between down and up strokes is approximately 1.5. Furthermore, the body pitch angle increased after the flapping angle reached 0deg during the down stroke and then decreased after the flapping angle reached 0deg during the upstroke. Thus, we hypothesized that controlling the ratio of the strokes made it possible to change body pitch angle that affected its posture.

Fig. 1  A butterfly as a model (left) and an example of successive pictures during takeoff (right)

Fig. 2  Definition of the physical parameters of a butterfly
2.2 Flapping mechanism for generating different stroke ratio

In order to generate the variation between down and up stroke times, we made a simple flapping mechanism based on a quick-return mechanism as shown in Fig. 4. This mechanism comprises three links. Link 1 rotates at a constant frequency and link 3 swings down and up. The time of these down and up strokes motions depends on the angle between link 1 and link 2, i.e., the ratio of angle $\alpha$ to angle $\beta$. For example, if the ratio of $\alpha$ to $\beta$ is 1/2 and the rotational direction of link 1 is clockwise, the ratio between up and down stroke times of link 3 is 1/2. Herein, if the rotational direction of link 1 is counter-clockwise in this case, the ratio between up and down stroke times of link 3 is 2/1. Figure 5 shows typical motions during down and up strokes.
2.3 Development of a butterfly-style flapping robot

We had developed a butterfly-style flapping robot that was equipped with a rubber motor as an actuator for high power-mass ratio [11], [12]. The slider-crank mechanism mounted on its rear translates the rotation of the actuator into the swing motion of the lower body around the pivot point (Fig. 6). This movement generates flexural deformation of the elastic links attached to the top of the lower body. This deformation generates a flapping motion of the wings.

We then developed new robot with quick-return mechanism instead of this previous flapping mechanism as shown in Fig. 7. The robot is constructed of carbon fiber reinforced plastic in order to be lightweight and possess high rigidity, and is equipped with a 4mm coreless motor. The wing membranes are 2μm thick films made of polyethylene. The flapping mechanism comprises of a spur gear (module 0.2) and a lower body. Link 1 in Fig. 4 corresponds to the length between the center of the spur gear and pin, link 2 corresponds to the length between the center of the spur gear and pivot point of the lower body, and link 3 corresponds to the lower body. The motor rotates the spur gear through

Fig. 5 An example of down stroke motion (left) and up stroke motion (right) for wings

Fig. 6 Flapping mechanism of a previous model
the worm gear, and the pin attached to the spur gear swings the lower body through the slider. This swing movement of the lower body generates flexural deformation of the elastic links attached to the top of the lower body in a similar way of previous flapping mechanism. This deformation generates a flapping motion of the wings. We adopted 100μm thick films made of polyethylene terephthalate for these elastic links because it has moderate elasticity. The amount of flexure of an elastic link depends on the amount of swing movement of the lower body. The wingspan and wing chord length are 114mm and 44mm, respectively. The total mass of the robot is 0.9g without the battery. The ratio between down and up stroke times was set to 1.5 based on the above analysis of a butterfly. Flapping angle was set to from 60 to -40deg. Note that this angle is smaller than that of a butterfly and our previous robot. This angle size of flapping depends on the amount of movement of the top of the lower body by swinging. In other words, if the amount of movement is large in this flapping mechanism, the angle size of flapping increases. In case of new flapping mechanism based on the quick-return mechanism, since this amount became smaller than that of previous mechanism, the angle size of flapping became smaller. Therefore, it is necessary to consider a method to increase the flapping angle in future research. Table 1 shows parameters of the links of the quick-return mechanism.

![Development of a butterfly-style flapping robot without battery](image)

**Table 1  Parameters of quick-return mechanism**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of link 1 [mm]</td>
<td>4.0</td>
</tr>
<tr>
<td>Length of link 2 [mm]</td>
<td>12.9</td>
</tr>
<tr>
<td>Length of link 3 (lower body) [mm]</td>
<td>35.0</td>
</tr>
<tr>
<td>Angle α [deg]</td>
<td>72</td>
</tr>
<tr>
<td>Angle β [deg]</td>
<td>108</td>
</tr>
</tbody>
</table>

**3 Experiments of flapping mechanism**

To demonstrate the capability of the flapping mechanism to generate different down and up stroke times, we analyzed the flapping motion of the developed robot by a high-speed camera (1280 × 1024 pixels at 1000fps, DITECT Co., Ltd.). In this experiment, the robot was fixed on a support pole for the following reasons: a) attenuate the vibrations in the body due to the movement of its wings and b) add supplied power (3.7V, 40mAh).
Figure 8 displays stroboscopic images of the robot during a flapping cycle. The down stroke occurred from 0 to 49ms and the upstroke occurred from 49 to 83ms. Its flapping frequency was approximately 12Hz. The transition of flapping angle is shown in Fig. 9 for two flapping cycles. Although the amplitude of both down and up stroke angles were low compared with those of a butterfly, the ratio between down and up stroke timings is similar to that of a butterfly in Fig. 3. The ratio between down and up stroke times is approximately 1.5, as designed. Analysis of the images showed that the developed flapping mechanism made it possible to generate a difference between down and up stroke times similar to that of a butterfly. Here, one of the reasons of the decrease in the flapping angle is flexural deformation of the wings by reaction force. To investigate of the influence of the wing deformation to the mechanism is a future work.

![Stroboscopic photographs of the under-development butterfly-style flapping robot captured during a flapping cycle](image)

**Fig. 8**  Stroboscopic photographs of the under-development butterfly-style flapping robot captured during a flapping cycle

![Transition of flapping angle of a butterfly-style flapping robot during two flapping cycles](image)

**Fig. 9**  Transition of flapping angle of a butterfly-style flapping robot during two flapping cycles
4 Numerical simulations of flight characteristics for different stroke ratio

4.1 Simulation models

In order to investigate a suitable ratio between down and up stroke times for the robot to fly, we first analyzed the relationship between the ratio and posture control mechanism of a butterfly by numerical simulation. Figure 10 outlines the simulation model of a butterfly. The body comprises four mass points, head, thorax 1, thorax 2, and abdomen, which are connected by springs and dampers. Both wings have their respective fore and hind wings integrated for synchronous movement. The total mass and length are obtained from observed values of butterflies. The coefficient of each spring and damper is set by a qualitative estimate of the motion of butterflies. The finite element method was used to calculate the body and wing motions and flow fields around the wings, whose details and qualitative validity have been previously documented [12], [13]. This simulation model is used to analyze flight characteristics such as flight trajectory and a shift in posture during flight.

![Diagram of simulation model](image)

**Fig. 10 Simulation model**

4.2 Setting parameters

In order to clarify how posture control is affected by the different ratios between down and up stroke times, three models were investigated based on the relationship between the ratio and the body pitch angle. The ratios between down and up stroke times of models A, B, and C are 1.5 (60%: 40%), 1.0 (50%: 50%), and 0.67 (40%: 60%), respectively. Model A’s ratio was the same as that of a butterfly and developed the robot. Model B is symmetric to Model A and Model C is a reverse model of A. Each model has flapping angle of 70deg to -60deg, an initial body pitch angle of 0deg, and a flapping frequency of 12Hz based on the observations of a butterfly. The wingspan and the wing chord length of each model are 118mm and 45mm, and the total mass of each model is 500mg, which is equivalent to that of a butterfly. The center of mass (COM) is located 19.3mm from the top of the head according to a butterfly. Therefore, the mass distribution (Head, Thorax 1, Thorax 2, and Abdomen) was calculated from total mass, COM, distances between mass points, and masses of abdomen and wings. Here, the mass of Thorax 2 is equivalent to that of Thorax 1. **Table 2 and 3 show the parameters. Table 4 shows experimental parameters of the three models.**
<table>
<thead>
<tr>
<th>Table 2  Masses of body and wings</th>
<th>Table 3  Lengths of the body</th>
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<tbody>
<tr>
<td>Mass [mg]</td>
<td>Length [mm]</td>
</tr>
<tr>
<td>Head</td>
<td></td>
</tr>
<tr>
<td>60.0</td>
<td>Length between Head and Thorax1</td>
</tr>
<tr>
<td>Thorax 1</td>
<td>4.0</td>
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<tr>
<td>75.0</td>
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<tr>
<td>Thorax 2</td>
<td>Length between Thorax 1 and 2</td>
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<td>10.0</td>
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<tr>
<td>Abdomen</td>
<td>Length between Thorax 2 and Abdomen</td>
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<tr>
<td>210.0</td>
<td>24.0</td>
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<tr>
<td>Wings</td>
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<tr>
<td>80.0</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>Total</td>
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<tr>
<td>500.0</td>
<td>38.0</td>
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</table>

<table>
<thead>
<tr>
<th>Table 4  Simulation parameters of three models</th>
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</thead>
<tbody>
<tr>
<td>Model A</td>
</tr>
<tr>
<td>Flapping angle [deg]</td>
</tr>
<tr>
<td>Flapping frequency [Hz]</td>
</tr>
<tr>
<td>Down/Up stroke cycle ratio</td>
</tr>
</tbody>
</table>

4.3 Results and discussion

Figure 11 shows comparisons of flapping and body pitch angles of models A, B, and C, respectively. Figure 12 shows a comparison of the trajectories of the centers of mass of the three models. Dashed and solid lines denote down and up strokes, respectively. Square and circular markers are used to depict the first and second ends of the flapping cycle, respectively.

There was a tendency for the body pitch angle to increase during the down stroke and decrease during the upstroke in each model. However, the body pitch angles of models A and B showed a general increasing tendency, whereas Model C showed a decreasing tendency. Here, we focus on the end of the first and second strokes. The body pitch angles of Model A (12.3deg and 71.7deg) were both greater than those of models B (6.6deg and 43.4deg) and C (-5.4deg and -34.1deg). Model C exhibited negative values, i.e., the posture of Model C was in a nose-down condition. In fact, when the ratio was high, the nose-up rotation became larger than the nose-down rotation during a cycle. Contrastingly, when the ratio was low, the nose-down rotation became larger than the nose-up rotation during a cycle. Figure 12 shows that Model A flew upward and Model B flew horizontally at the end of second stroke, whereas Model C flew downward.

Analysis of the vertical and horizontal distances of the first flapping cycle of each model is considered here. Models A and B flew upward during down stroke, and then downward during upstroke. Their heights at the end of upstroke were 10.2mm and 18.3mm, respectively. In contrast, although Model C flew downward during upstroke (similar to models A and B), the height at the end of upstroke was higher than that of down stroke. Horizontal distances of each model were 29.7, 36.7, and 48.6mm, respectively. Therefore, the ratios of horizontal to vertical distances of these were 2.9, 2.0, and 1.7, respectively. Thus, the ratio of horizontal flight of Model A was higher than that of the others during the first flapping cycle.

The vertical and horizontal distances of the second flapping cycle were also similarly analyzed. Model A fell to -11.7mm during down stroke and then flew upward to 12.5mm, and Model B flew from 3.9mm to 24.7mm. In contrast,
although Model C flew upward from 19.5mm to 32.7mm during down stroke, fell to 2.1mm during upstroke. Vertical
distances of each model from the lowest point during down stroke to the end of two flapping cycles were 25.2mm of
Model A, 20.9mm of Model B, and -17.0mm of Model C. Since the horizontal distances of each model were 50.0mm,
71.7m, and 100.2mm, respectively, the ratios of the horizontal to vertical distances were 2.18, 3.43, and -5.89,
respectively. Therefore, the ratio of vertical flight to horizontal flight of Model A was higher than that of models B and
C during second flapping cycle.

Since Model A exhibits nose-up rotation and Model C exhibits nose-down rotation, the results indicated that a
butterfly tended to fly upward when the down stroke time was longer than that of upstroke, and vice versa in the
opposite case. Therefore, the ratio between down and up strokes of the butterfly-style flapping robot needs to set to 1.0
or more for upward flight and set to less than 1.0 for downward flight. In these experiments, however, we did not
analyze these characteristics quantitatively such as lift, drag, and body pitch moment. Hence, it is necessary to analyze
the flight characteristics affected by the ratio between down and up strokes.

![Graphs of Models A, B, and C](image-url)

**Fig. 11** Relation between flapping and body pitch angles of models A, B, and C
5 Conclusions

In order to achieve posture control of a butterfly-style flapping robot, we developed a flapping mechanism that generated different ratio between down and up stroke times based on a quick-return mechanism. Furthermore, we demonstrated the validity of the mechanism by performing experiments and analyzing the flight characteristics using numerical simulations for three models. These results showed that the body pitch angle tends to increase as the time of the down stroke becomes longer than the upstroke time. In contrast, the body pitch angle tends to decrease as the time of the down stroke becomes shorter than the upstroke time. This is in agreement with simulation results of a butterfly, which exhibited upward flight tendency when the down stroke time was longer than that of upstroke, and vice versa. It is clear that the down stroke time needs to be longer for upward flight and the upstroke time needs to be longer for downward flight.

In future research, we aim to perform further quantitative analyses of the flight characteristics of flying robots in order to understand the effect of different ratios between down and up stroke times on the lift, drag, and body pitch moment.

Acknowledgments

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References